Overview of Theory Program

David Richards

Science and Technology Review
14th July, 2009

Vadim Guzey → Breakout Session
Outline

• Members
• Role of Theory Center
• Highlights – *outstanding new results in*
  • *Spectrum of QCD*
  • *Hadron Structure*
  • *Physics of Nuclei*
  • *Physics beyond the Standard Model*
• Theory Campaigns:
  • EBAC
  • Lattice QCD
  • EIC
• Summary
JLab Theory Center: Senior Staff

• Chief Scientist / Theory Director: Anthony Thomas

• 5 Laboratory staff (4.5 FTE)
  - Robert Edwards  lattice gauge theory
  - Franz Gross  (1/2 time)
  - Wally Melnitchouk  phenomenology
  - David Richards  Deputy Director (lattice gauge theory)
  - Christian Weiss  phenomenology

Distinguished Visitors: W. Bentz, M. Burkardt, F. Close, R. Crewther, V. Flambaum, Harald Fritzsch, P. Guichon, J-M Laget, D. Leinweber, G. Miller, M. Peardon, T. Pena, S. Ryan, A. Sibirtsev, A. Stadler,…

• 8 staff with joint appointments (4.0 FTE → 50 % Lab support)
  - Ian Balitsky (ODU)  Jozef Dudek (ODU)
  - Jose Goity (Hampton)  Rocco Schiavilla (ODU)
  - Kostas Orginos (W&M)  Anatoly Radyushkin (ODU)
  - Wally van Orden (ODU)  Will Detmold (W&M)
Associate Senior Staff: Carl Carlson (W&M)

Bridge Positions
- University of Virginia (Chris Dawson)
- Hampton University (Andrei Afanasev)
- University of Connecticut (Peter Schweitzer)

5 JLab postdoctoral fellows (5 FTE)
- Huey Wen Lin – since Fall 06 → 5-year at Univ. Washington
- Marc Schlegel - since Fall 06 → PDF at Tübingen
- Ping Wang - since Fall 07 → faculty at IHEP, Beijing
- Vadim Guzey – since Fall 07
- Chris Thomas – since Fall 08

Isgur Distinguished Postdoctoral Fellow
- Alessandro Bacchetta – since Mar 08 → faculty at Pavia

Joint post-doctoral position in phenomenology with Hampton Univ.
- Alberto Accardi

Joint post-doctoral position in LQCD with Adelaide
- Andre Sternberg
Key Roles of Theory at JLab

• Contribute to Intellectual Leadership of Lab
  – Success of 12 GeV; Preparing for EIC
• Support of Experimental Program @ 6 GeV
  - development/analysis of proposals; interpretation of data
• Projects of large scope/duration: EBAC, Lattice QCD
• Education
  – 9 graduate students (6 supported by JLab)
    • Giovanni Chirilli: JSA/Jefferson Lab Graduate Fellowship 2008-9
    • Ian Cloet: shared 2008 SURA Thesis Prize
  – HUGS (Hampton University Graduate School).
  – Virginia Physics Consortium – Graduate-level course in Hadronic Physics (Wally Melnitchouk)
  – Theory-Center mini-lectures (Bacchetta)
  – High-school Mentorships
  – Science Undergraduate Laboratory Internship (SULI)
    • 2008: Tim Hobbs and Yoni Kahn (Wally Melnitchouk)
    • 2009: Hannes Schimmelpfennig
  – RIFU
    • 2008: Ermal Rrapaj (Jo Dudek)

Joint Positions Vital

Hobbs: First prize in Users Group poster competition
Distinguished Members

- 8 Fellows of the American Physical Society;
- 1 Fellow Australian Academy of Science and Institute of Physics;
- Serve on IAC of all major conferences and workshops in related fields;
- Organization and planning of major workshops:
- Tony Thomas chairs IUPAP Working Group (WG.9) on International Cooperation in Nuclear Physics;

Will Detmold - 2009 OJI - “Multi-Meson Systems in Lattice QCD”
Excited Baryon Analysis Center

- Analyse wealth of experimental data on baryon resonance production at Jlab and elsewhere
- Goal: ensure that the OMB Milestones in Hadronic Physics are satisfied:
  - HP2009: Complete the combined analysis of available data on single \( \pi, \eta, \) and \( K \) photo-production of nucleon resonances and incorporate the analysis of two-pion final states into the coupled-channel analysis of resonances.
  - HP2012: Measure the electromagnetic excitations of low-lying baryon states (<2 GeV) and their transition form factors over the range \( Q^2 = 0.1 \) – 7 GeV\(^2\) and measure the electro- and photo-production of final states with one and two pseudoscalar mesons.
- Led by Harry Lee (ANL/Jlab)
- Three Post-doctoral Fellows
  - Mark Paris \( \rightarrow \) GWU
  - Hiroyuki Kamano (since Fall 2007)
  - Kazuo Tsushima (since Fall 2007)
  - Satoshi Nakamura (from Fall 2009)
Continuing high productivity

<table>
<thead>
<tr>
<th>Types of Publications</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>To Appear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phys Rev Lett and Phys Lett</td>
<td>13</td>
<td>16</td>
<td>11</td>
<td>13</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Other Refereed Journals</td>
<td>84</td>
<td>41</td>
<td>47</td>
<td>56</td>
<td>31</td>
<td>18</td>
</tr>
<tr>
<td>Invited Talks in Conf. Proc Published</td>
<td>14</td>
<td>10</td>
<td>15</td>
<td>15</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Invited Talks in Conf. Proc. Not Published</td>
<td>28</td>
<td>60</td>
<td>69</td>
<td>109</td>
<td>17</td>
<td>18</td>
</tr>
<tr>
<td>Instrumentation Papers</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Contributed Papers</td>
<td>15</td>
<td>13</td>
<td>24</td>
<td>11</td>
<td>1</td>
<td>6</td>
</tr>
</tbody>
</table>
Highlights

• Themes
  • The Spectrum of QCD
  • The Structure of Hadrons in QCD
  • The Physics of Nuclei
  • The Standard Model and Beyond
How quarks and gluons form hadrons and nuclei

The Spectrum of QCD
Lattice QCD and Baryon Spectrum

Nucleon Mass Spectrum (Exp)

Hadron Spectrum Collaboration, arXiv:0901.0027

Lattices generated at ORNL under INCITE

Emergence of pattern seen in experiment!
GlueX intends to photoproduce meson resonances

- Major motivator is the search for mesons with exotic $J^{PC}$ quantum numbers - believed these can arise from excitation of the gluonic field (hybrids)

- Model calculations suggest that exotic photocouplings can be large - can lattice QCD weigh in on this?

Similar physics in radiative transitions (at CLEO-c, BES, PANDA ...) charmonium (heavy quarks) is a simple test-bed for the calculations

- In charmonium there are relatively successful non-relativistic potential models - can verify these and go beyond making statements about the excited glue without model assumptions
Preparing for GlueX: Radiative Transitions


Use of variational method, and the optimized meson operators, to compute radiative transitions between excited states and exotics.

\[ \Gamma(\eta_{c1} \to J/\psi \gamma) \approx 100 \text{ keV} \]

considerable phenomenology developed from the results - supports non-relativistic models and limits possibilities for form of excited glue

Radiative width of hybrid comparable to conventional meson – important for GlueX
Anisotropic Clover Lattice Generation

• “Clover” Anisotropic lattices $a_t < a_s$: major gauge generation program under INCITE and discretionary time at ORNL designed for spectroscopy

Novel way of specifying quark masses and scale

Low-lying hadron spectrum

Lattice Roadmap for Spectroscopy

“Extreme Scale” Computing Workshop,
Jan 26-28, 2009

- Spectrum and properties of mesons
- Nucleon transition form factors
- Spectrum and photo-couplings of isovector mesons
- Cascade Spectrum
- N* Spectrum
- Photocouplings in charmonium

10x tera 100x tera peta 10x peta 100x peta 1 Exa-flop year

GlueX

Thomas Jefferson National Accelerator Facility
EBAC: extract and Interpret N*
Accomplishments

- Dynamical coupled-channel analysis of $\pi N \rightarrow \pi N$, $\pi \pi N$ reactions.
- Dynamical coupled-channel analysis of electromagnetic $\pi$ production reactions.
- Extraction of nucleon resonances from dynamical coupled-channel model.

Plans

- Combined coupled-channel analysis
- Amplitude extractions from complete measurements
- Connection with hadron-structure calculations
Progress in 2008-2009 - I

- Complete analysis of $p(\pi, 2\pi)N$ data
  Red: no coupled-channel
- Obtain fits of CLAS $p(e, e'\pi)N$ data
  Dashed: no coupled-channel
  Clear evidence of coupled-channel effects
Progress in 2008-2009 - II

Extraction of nucleon resonances from dynamical coupled-channel model

Trajectories of extracted resonance poles

$P_{11}$ resonances, extracted within EBAC-CC model

New information on interpreting Roper

*Suzuki et al (Kamano, Lee), submitted to PRL*
How quarks and gluons form hadrons and nuclei

Hadron Structure
Theory Support for “GPD” Program

- **GPDs and nucleon structure**
  - Nucleon imaging and polarization effects [Burkardt]
  - Chiral dynamics at large distances [Weiss]
  - GPD/TMD connection [Schlegel, Bacchetta]
  - Model calculations [Schweitzer]
  - Orbital angular momentum [Thomas]
  - Lattice calculation of GPD moments [--> Lattice]

- **Extracting GPDs from DVCS/meson production data**
  - DVCS: t-channel based GPD parametrizations [Guzey]
  - DVCS: Nuclear targets [Guzey]
  - Meson production: Reaction mechanism, finite-size effects
    - ("higher twist"), model-independent comparative studies [Weiss]
  - GPDs in pp scattering [Weiss]

- **Communication/representation:** Working Group meetings
  (experiment + theory), topical lectures, strong representation at international conferences, contributions to 2007 NSAC LRP
Medium modifications of bound nucleon GPDs


Jlab expt. DVCS on $^4$He

Coherent

incoherent
Transverse Momentum Distributions

Bacchetta et al

Sivers’ Effect

Tomographic images of nucleon in momentum space
Example of extraction from experiments

Fits based on HERMES and COMPASS single-spin asymmetries in semi-inclusive DIS. Similar measurements are a large component of the future Jlab@12GeV plans

Arnold, Efremov, Goeke, Schlegel, Schweitzer, arXiv:0805.2137
See also work by A. Prokudin, future post-doc at JLab
Connections between TMDs and GPDs

GTMD (Generalized Transverse Momentum Distribution)
“mother distribution”

\[ F(x, \xi, k_T^2, k_T \cdot \Delta_T, \Delta_T^2) \]

\[ \int d^2 k_T \]

\[ H(x, \xi, t) \rightarrow \xi = 0, \Delta_T = 0 \]

Model-dependent connections

GPD

Meissner, Metz, Schlegel, arXiv:0906.5323

TMD
Higher-twist effects from $g_2$

- Sizeable higher-twist terms $\sim 15\text{-}40\%$ can be isolated in $g_2$: 
  
  $$g_2(x) = g^\text{WW}_2(x) + g^\text{HT}_2(x)$$
  
  $$g^\text{WW}_2 = -g_1 + \int_x^1 \frac{dy}{y} g_1(y)$$
  
  $$g^\text{HT}_2 = \tilde{g}_T - \int_x^1 \frac{dy}{y} \tilde{g}_T(y) + \int_x^1 \frac{dy}{y} \tilde{g}_T(y)$$
  
  "Wandzura-Wilczek relation"

- 2 different contributions to $g^\text{HT}_2$
  - can be separated by measuring $g_{1T}$ in double LT spin asymmetries
  
  $$\tilde{g}_T(x) = g_2(x) - \frac{d}{dx} \int d^2k_T \frac{k_T^2}{2M} g_{1T}(x, \vec{k}_T)$$

- Preliminary data on $g_{1T}$ coming soon from Hall A
Lattice QCD

- Lattice group has major effort in understanding *nucleon* structure: Moments of GPDs and structure functions, Form Factors,…
- Extending to other flavor sectors

**Flavor “off-forward” GPDs**

**Octet baryon axial-vector couplings**

![Graph showing axial-vector couplings](image)

**Octet baryon charge radii**

![Graph showing charge radii](image)


P Wang, A Thomas et al., arXiv:0810.1021
Lattice QCD Roadmap

- Gluon contributions to hadron structure
- Form factors up to scaling region
- High precision axial charge
- Isovector form factors and moments of generalized parton distributions
- Individual contributions of up, down, and strange quarks to hadron structure

Jlab @ 12GeV

1 Exa-flop year
Pion Form Factor – Holographic QCD

- Simple analytic result
  \( F_\pi(Q^2) = \frac{4}{Q^2z_0^2} \left[ 1 - \frac{1}{I_0(Qz_0)} \right] \)


- Pion charge radius
  \( \langle r^2_\pi \rangle_{\text{AdS/QCD}} = \frac{9}{8} z_0^2 \approx 0.42 \text{ fm}^2 \)

- Experiment: \( \langle r^2_\pi \rangle \approx 0.45 \text{ fm}^2 \)

- Large-\( Q^2 \) behavior:
  \( Q^2 F_\pi(Q^2) \to \frac{4}{z_0^2} \approx 0.42 \text{ GeV}^2 \)

- Anomalous form factor \( \pi^0 \gamma \gamma^* \) in this model is given by the same expression

- Slope \( a_\pi \equiv -m_\pi^2 \left[ \frac{dF_{\gamma^*\pi^0}(Q^2)}{dQ^2} \right]_{Q^2=0} \)

  \[ = \frac{3}{16} m_\pi^2 z_0^2 \approx 0.035 \]

- Experimentally
  \( a_\pi = 0.026 \pm 0.024 \pm 0.0048, \)
  \( a_\pi = 0.025 \pm 0.014 \pm 0.026 \) (1992)

  Interesting to measure in modifications of PRIMEX
New *BaBar data (May 2009)* indicate no flattening of $\gamma\gamma^*\pi$ form factor

Model for light-front pion wave function that is consistent with flat leading-twist pion distribution amplitude

Such a model can describe *BaBar high-Q^2 data.*

Asymptotic pQCD calculation.

Lattice calculation consistent with such a form

*A Radyushkin, arXiv:0906:0323*
How nucleons bind together to form nuclei

Physics of Nuclei
How nucleons bind together to form nuclei

Variety of approaches:
– Constructing nuclear interactions and currents:
  • One-boson-exchange phenomenology and similar (Gross, Schiavilla, Van Orden)
  • Effective field theory approach (A. Thomas)
  • Hadronic interactions in Lattice QCD (Detmold, Orginos)
– Structure and reactions of nuclei:
  • Relativistic approaches to nuclear dynamics (Gross, Schiavilla, A. Thomas, Van Orden)
  • Form factors and weak transitions in few-nucleon systems (Gross, Schiavilla, A. Thomas, Van Orden)
  • EFT studies of the structure of few-nucleon systems (Gross, Schiavilla)
  • Nuclear reactions of astrophysical interest (Schiavilla)
  • Nuclear effects on nucleon properties V. Guzey
Lattice QCD for Nuclear Physics

Kaon condensation

Isospin
Chemical potential

\[ \frac{\mu_{K^-}}{m_K} \]

\[ \mu_{K^-} - 1 \]

\[ (2.5 \text{ fm})^3 \rho_{K^-} \]

NPLQCD (Detmold, Orginos): PRL 100, 082004 (2008); PRD 77, 057502 (2008); PRD 78, 014507 (2008); PRD 78, 054514 (2008)
Three-baryon system

Relative uncertainty in ground-state energy

Feasibility of extracting three-nucleon interaction demonstrated

NPLQCD (Detmold, Orginos), arXiv: 0905.0466

\[ \delta E_{\Xi\Xi n} = 4.6 \pm 5.0 \pm 7.9 \pm 4.2 \text{MeV} \]
Standard Model and Beyond
Axion Search: LIPSS

- *`Dark matter puzzle’*: Cosmology and recent data from space telescopes provide evidence that most of the mass of the observable universe cannot be associated with any of the known Standard-Model elementary particles.
- **Axions** - hypothetical particles proposed to solve a strong CP problem in Quantum Chromodynamics - are dark matter candidates.

“Light shining through a wall…”

- **Theoretical idea**: Sikivie (1983); Ansel’m (1985); Van Bibber et al (1987)
- **First limits on axion-photon mixing obtained by BFRT Collab, (BNL,1993)**
- **Implemented at JLAB FEL by LIPSS Collaboration (2007-present)**

![Diagram of light shining through a wall](image.png)

**LIGHT BEAM** experiment that would confirm the existence of axions passes a laser beam through a strong magnetic field, converting some photons to axions [green beam]. The axions penetrate a wall before passing through another magnetic field that converts some of the particles back to photons, which form an extremely faint spot on the far wall.
Published LIPSS Result


- No signal observed, regions above curves excluded by the experiment
- LIPSS reached the sensitive region for scalar coupling
- In agreement with other measurements: BFRT, GammeV, BMV

BSM Physics: mixing between photons and paraphotons.

Afanasev et al, arXiv:0810.4189
EFT Fits to Lattice Data

- Stress: This involves just 4 SU(3) parameters plus $\Lambda$, fit to lowest 8 data points
- There is a great deal of physics to be extracted from this fit

Young & Thomas, arXiv:0901.3559 [nucl-th]
Summary Fits to LHPC and CP-PACS

Of particular interest:

\[ \sigma \text{ commutator well determined: } \sigma_{\pi N} = 51 \ (6) \ (2) \ (2) \text{ MeV} \]

and strangeness sigma commutator small

\[ m_s \frac{\partial M_N}{\partial m_s} = 18 \ (10) \ (6) \ (3) \text{ MeV} \]

\text{NOT several 100 MeV!}

Profound Consequences for Dark Matter Searches
Hadronic Uncertainties in the Elastic Scattering of Supersymmetric Dark Matter

John Ellis,1,* Keith A. Olive,2,† and Christopher Savage2, ‡

CERN-PH-TH/2008-005
UMN-TH–2631/08
FTPI–MINN–08/02

We find that the spin-independent cross section may vary by almost an order of magnitude for $48 \text{ MeV} < \Sigma_{\pi N} < 80 \text{ MeV}$, the $\pm 2$-$\sigma$ range according to the uncertainties in Table I. This uncertainty is already impacting the interpretations of experimental searches for cold dark matter. Propagating the $\pm 2$-$\sigma$ uncertainties in $\Delta_{s}^{(p)}$, the next most important parameter, we find a variation by a factor $\sim 2$ in the spin-dependent cross section. Since the spin-independent cross section may now be on the verge of detectability in certain models, and the uncertainty in the cross section is far greater, we appeal for a greater, dedicated effort to reduce the experimental uncertainty in the $\pi$-nucleon $\sigma$ term $\Sigma_{\pi N}$. This quantity is not just an object of curiosity for those interested in the structure of the nucleon and non-perturbative strong-interaction effects: it may also be key to understanding new physics beyond the Standard Model.

\[
\mathcal{L} = \alpha_{2i} \bar{\chi} \gamma^{\mu} \gamma^{5} \chi \bar{q}_i \gamma_{\mu} \gamma^{5} q_i + \alpha_{3i} \bar{\chi} \chi \bar{q}_i q_i
\]
Opportunities beyond 12 GeV: EIC

- EIC Collaboration (BNL & JLab, since 2007):
  Substantial JLab Theory involvement

  - $ep/eA$ Physics Working Group Conveners
  - Models for physics simulations; conceptual development
  - EIC Workshops: Stony Brook 07, Hampton 08, Berkeley 08
  - Representation at international conferences: DIS 07/09, Trento 08, INT 09
  - White Paper for 2007 LRP

- New development (2008): Medium-energy $ep/eA$ collider for nuclear physics at JLab

  - Natural extension of 12 GeV nucleon structure/QCD program
  - Conceptual/technical development in co-operation with CASA group and JLab users

- Future: Expand/intensify collider R&D effort

  - Exciting opportunities: Sea quarks, gluons, spin, QCD vacuum, nuclei in QCD, . . .
  - Theory input essential for physics program, simulations
  - Depends critically on Lab staff!
Lattice QCD

- Jefferson Laboratory partner with BNL and FNAL in lattice QCD effort.

  **FNAL**
  - Weak matrix elements

  **BNL**
  - RHIC and HEP

  **JLAB**
  - Hadronic Physics

  **SciDAC - R&D Vehicle**

Close (two-way) connection with HPC Group
- Balint Joo, Saul Cohen vital to theory effort
- Robert Edwards vital to software effort

Lattice QCD at JLab has major impact on DOE’s Nuclear Physics Program
- $5M ARRA for LQCD
Summary

• JLab Theory Center has major impact in **inspiring, facilitating, and interpreting** the JLab program at both 6 and 12 GeV and preparing for EIC.

• Recent initiatives coming to fruition – Lattice QCD, EBAC; new theoretical focus on large-x structure functions

"Sir, I have found you an argument; but I am not obliged to find you an understanding. “ – That’s where theorists are useful…

Boswell's Life of Johnson